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Development of Low Cost Motion-sensing System

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Abstract

Micro-electro-mechanical system (MEMS) technology offers sensors with lower cost, smaller size, lower power consumption. In this paper, a kind of low cost motion-sensing system based MEMS sensors is described. The objective of the design is low cost, small volume and light weight in order to be used in many fields. The constituting principle of the system is described. Algorithms and hardware of the system are researched. And the definitions of coordinate, calculation of pose angle, transform of acceleration and calculation of the velocities and displacement of the moving object are presented with corresponding mathematics model and algorithms. The experiments are carried out in principle and results are given. It is proved that the low cost motion-sensing system is effective and correct.

1. Introduction

Motion sensing is not a new idea. Autonomous motion sensing has also existed for quite some time. Robots, aircraft, automobiles, and other vehicles have sensed and measured their motions for decades, using varying electromechanical sensors as well as inertial sensors [1–3]. Because other sensing modes such as infrared, radar, video motion-sensing technologies and so on are subject to occlusions and numerous interferences and noise sources, a more tractable and generally effective type of motion sensor is the inertial sensor. Two types of sensors comprise inertial sensing: accelerometers and gyroscopes. This type of sensor attaches directly to the moving body of interest and gives an output signal proportional to its own motion with respect to an inertial frame of reference. Because they operate regardless of external references, friction, winds, directions, and dimensions, inertial sensors are desirable for general motion sensing.

Until recent years, inertial sensors have only found use in the few fields mentioned above, since their cost and size have traditionally been quite prohibitive. Recent advances in MEMS technologies have enabled inertial sensors to become available on the small size and price scales associated with such commonplace devices as consumer appliances. Micro inertial sensors have been the subject of intensive research for over two decades since Roylance et al. [4] reported the first MEMS accelerometer in 1979. Since then many authors have published work about various types of micro inertial sensors [5–8]. The commercial inertial market shows a number of prevalent inertial sensor technologies including piezoelectric, piezoresistive, and capacitive accelerometers and vibrational gyroscopes. These sensors are shrinking in size and price and are becoming useful. Accelerometers and gyroscopes are available for tens of dollars a piece and on the size scale of a pen cap [9, 10]. Table 1 gives us cost, size and performance about several gyroscopes from the 1970s to 1990s.

This paper develops a low cost motion-sensing system by means of micro accelerometers and micro gyroscopes. Instead of a high performance inertial sensor, our primary sensors are low-cost inertial ones. The aim of the low cost motion-sensing system is to track the six degrees of freedom of the object of interest. In this way, the position and orientation of the object can be known. Such a system finds application in many areas such as the military, space exploration, industrial intelligent robots, vehicles, and even in toys. It measures linear accelerations and angular rates of moving objects by accelerometers, gyro, etc. Then some navigation parameters such as positions, velocities, poses and so on are gotten through algorithms in the computer. The system does not radiate any energy to circumstance and not depend on any other information outside when it measures. Thus, it has advantages of autonomy, work in the any weather, anti-jamming character.

2. Principle of the System and Constitution

2.1. Principle of the System

The low cost motion-sensing system performs the measurement of six dimensional movement parameters (pitch, yaw, roll, the accelerometer in X, Y and Z axis separately). The combination of micro accelerometers, gyroscopes, signal processing circuits and signal conditioning circuits make possible the combination parameter measurement of moving objects. Fig. 1 presents a sketch map of the sensitive head. The angular rate information is gained by micro gyroscopes, and acceleration information by micro accelerometers. The attitude, velocity and displacement of objects relative to certain fixed coordinate could be obtained by coordinate conversion.
2.2. Principle of Inertial Sensors Used in the System

Because the system is made up of micro accelerometers and micro gyroscopes, it is low cost, miniature size and extremely light weight.

A gyroscope is a device which measures the rotating rate or whole angle displacement. MEMS gyroscopes typically use vibrating structures because of the difficulty of micromachining rotating parts with sufficient mass to be useful. Its current structure consists of quartz and silicon vibrating beam. The quality factors of quartz material structure are high. The performance of gyroscope is excellent and is early commercialized. Vibrating gyroscopes include tuning forks, vibrating beam, vibrating shells, and others. The difference of different MEMS gyroscopes lies in the vibrating device. Electro-static, electromagnetic and piezoelectric vibrating devices are the currently used.

The principle of vibrating gyroscope is based on the Coriolis effect. If there is rotational $\omega$ about the $X$ axis, the Coriolis force will occur in the $Z$ axis when the centre masses vibrate in the same direction along the $Y$ axis. Coriolis force is given by:

$$ F_C = 2mv \times \omega $$

$$ M_C = 2mrv \times \omega $$

where $v$ is the vibrating velocity of vibrator, $\omega$ is the rotational angular velocity, $F_C$ and $M_C$ are Coriolis force and Coriolis force momentum separately.

For MEMS accelerometer, there are several types, such as piezoresistive, capacitive, resonant-beam, piezoelectric sensors and so on. Fig. 2 (a) is simplified view of the Analog Devices’ capacitive MEMS acceleration sensor at rest. The two capacitors are series connected, forming a capacitive divider with a common movable central plate. The sensor’s fixed capacitor plates are driven differentially by a square wave. When at rest, the values of the two capacitors are the same, and therefore, the voltage output at their electrical center is zero. Fig. 2 (b) shows the sensor responding to an applied acceleration. When this occurs, the common central plate or “beam” moves closer to one of the fixed plates while moving further from the other. This creates a mismatch in the two capacitances, resulting in an output signal at the central plate. The output amplitude of the signal varies directly with the amount of acceleration experienced by the sensor [7].

2.3. Constitution of the System

The low cost motion-sensing system is made up of two dual-axis solid-state micro rate gyros, two dual-axis micro accelerometers, amplifier, conditional circuit, filter, voltage regulator, etc. MG100 and ADXL202 being inertial sensors are chosen. The A/D converter is 12 bits, high speed A/D data acquisition card with 32 channels. Its highest convert speed is 100KHz.

Fig. 3 depicts an overall structure of the system. First, linear accelerations and angular rates of a moving object are measured by micro accelerometers and micro gyro. Second, the data are acquired by a high speed A/D data acquisition card of computer through an antialias filter. Third, the analysis of pose and position information of the object is completed with software, and its results are stored in the form of files.

Fig. 4 gives us a photo of the low cost motion-sensing system. Its volume is $110 \times 66.8 \times 37.6$ mm$^3$ with 146.1 grams.
angle, \( \phi \) denotes yaw axis angle, \( \theta \) denotes pitch-axis angle.

From

\[
x'i + y'j + z'k = q^{-1}(xi + yj + zk)q
\]

we can obtain equation (3).

\[
\begin{pmatrix}
x' \\
y' \\
z'
\end{pmatrix} =
\begin{pmatrix}
T_{11} & T_{12} & T_{13} \\
T_{21} & T_{22} & T_{23} \\
T_{31} & T_{32} & T_{33}
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
\]

where

\[
\begin{align*}
T_{11} &= \lambda^2 + \rho_1^2 - \rho_2^2 - \rho_3^2 \\
T_{12} &= 2\rho_1 \rho_2 + \lambda \rho_3 \\
T_{13} &= 2\rho_1 \rho_3 - \lambda \rho_2 \\
T_{21} &= 2\rho_1 \rho_2 - \lambda \rho_3 \\
T_{22} &= \lambda^2 - \rho_1^2 + \rho_2^2 - \rho_3^2 \\
T_{23} &= 2\rho_1 \rho_3 + \lambda \rho_2 \\
T_{31} &= 2\rho_1 \rho_3 + \lambda \rho_2 \\
T_{32} &= 2\rho_1 \rho_2 - \lambda \rho_3 \\
T_{33} &= \lambda^2 - \rho_1^2 - \rho_2^2 + \rho_3
\end{align*}
\]

Based on the definition of directional cosine matrix. The following formulae are defined.

\[
\begin{align*}
T_{11} &= \cos \phi \cos \theta \\
T_{12} &= \sin \phi \cos \theta \\
T_{13} &= -\sin \phi \\
T_{21} &= \cos \phi \sin \theta \sin \gamma - \sin \phi \cos \gamma \\
T_{22} &= \sin \phi \sin \theta \sin \gamma + \cos \phi \cos \gamma \\
T_{23} &= \cos \phi \sin \gamma \\
T_{31} &= \cos \phi \sin \theta \cos \gamma + \sin \phi \sin \gamma \\
T_{32} &= \sin \phi \sin \theta \cos \gamma - \cos \phi \sin \gamma \\
T_{33} &= \cos \theta \cos \gamma
\end{align*}
\]

Thus, pose angles can be obtained by processing equations above. They are as follows.

\[
\begin{align*}
\theta &= -\sin^{-1}\left(\frac{T_{13}}{\rho_1}\right) \\
\gamma &= \tan^{-1}\left(\frac{T_{23}}{T_{22}}\right) \\
\phi &= \tan^{-1}\left(\frac{T_{12}}{T_{11}}\right)
\end{align*}
\]

Because \( \gamma \) is in \([-180^\circ, 180^\circ]\) and \( \phi \) is in \([0^\circ, 360^\circ]\), we must judge which area the angles should lie in.

### 3.3. Transform of Acceleration

We can get immediately accelerations of inertial space from sensors. But we have to know accelerations to the earth coordinate and to the geographical coordinate. So we need transform the accelerations from one coordinate to another one in order to realize navigation. Equation (4) is a transform method from the inertial coordinate to the geographical coordinate.

\[
\begin{pmatrix}
a_E \\
a_N \\
a_T
\end{pmatrix} =
\begin{pmatrix}
a_e \\
a_n \\
a_t
\end{pmatrix} +
\begin{pmatrix}
\omega_E \\
\omega_N \\
\omega_T
\end{pmatrix}
\times
\begin{pmatrix}
v_E \\
v_N \\
v_T
\end{pmatrix}
\]

where \( \begin{pmatrix} a_E \ a_N \ a_T \end{pmatrix}^T \) is the accelerations relative to the inertial space, \( \begin{pmatrix} v_e \ a_n \ a_t \end{pmatrix}^T \) is the accelerations relative to the geographical reference frame, \( \begin{pmatrix} 0 \ a \ m^{-2} \end{pmatrix}^T \) is the components of the gravitational accelerations in the geographical reference frame, \( \begin{pmatrix} v_e \ v_n \ v_t \end{pmatrix}^T \) is the velocities relative to the geographical reference frame, \( \begin{pmatrix} \omega_E \ \omega_N \ \omega_T \end{pmatrix} \) is the self-rotating angular rates of the earth.

### 3.4. Calculation of the Velocities and Displacement of the Moving Object

Through the transformation of the acceleration, the accelerations to the earth surface of the moving object can be obtained. After the integral operation, we can get the velocities and the displacement relative to the earth surface.

### 4. Software of the System

Using MFC software, a user interface of the system is designed. It is shown in Fig. 5. In Fig. 5, three frames each named system data, velocity & motion and attitude display different values of different information. In the right of the figure, there is a graphics interface similar to a control board of a plane that can give displacement images of horizontal movement and vertical movement. By the graphics interface, we are able to know distinctly many data of moving object. For example, the trace of object will be displayed through the horizontal line with scale in the top. At the same time, the vertical line with scale in the left means velocity information and another one in the right means height information. In the middle, there are a rotor hand like a trigonal wave and a scalariform scale. The former denotes the roll direction. The latter expresses the roll data.

User can finish interactive manipulation by pressing some buttons in pop-up menu or in direct interface and giving some orders, such as start, stop, initialize, zero and so on.
5. Experiment and Result

Not changing yaw-axis and pitch-axis angles, and only changing roll-axis angles, we got some measurement results. Table 3 is the experiment result of roll-axis angles. From Table 3, it is given that minimal measurement error of roll-axis angles can reach 0.1656 degree in a typical instance.

<table>
<thead>
<tr>
<th>Measurement value (degree)</th>
<th>Theory value (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7831</td>
<td>9</td>
</tr>
<tr>
<td>17.8344</td>
<td>18</td>
</tr>
<tr>
<td>27.3244</td>
<td>27</td>
</tr>
<tr>
<td>37.1549</td>
<td>36</td>
</tr>
<tr>
<td>43.1629</td>
<td>45</td>
</tr>
<tr>
<td>50.7307</td>
<td>54</td>
</tr>
<tr>
<td>58.0471</td>
<td>63</td>
</tr>
<tr>
<td>70.1203</td>
<td>72</td>
</tr>
<tr>
<td>77.7366</td>
<td>81</td>
</tr>
<tr>
<td>88.2593</td>
<td>90</td>
</tr>
<tr>
<td>-0.1840</td>
<td>0</td>
</tr>
</tbody>
</table>

6. Conclusions

Based on micro inertial sensors, the principle, structure and arithmetic realization of low cost motion-sensing system are discussed in the paper. Through experiment, we know that the system is correct and effective.

The work presented is part of an ongoing research project and we hope in the near future to have all computation and sensor processing onboard. Work is also underway to more closely integrate the inertial sensors and algorithm. In order to allow the new device to be applied in many field, MEMS inertial sensor manufacturers need to continue their current trend of making smaller, cheaper, and higher accurate sensors (0.1~1 deg/hr) in the near future.

Acknowledgments

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References

[2] Miller, B. L., Use of the NAVSTAR global positioning system to update the inertial navigation system of carrier-based aircraft, NSWC/DL TR3437, Dahlgren, Virginia, March 1976
[7] Analog Devices, ±1g to ±5g single chip accelerometer with signal conditioning-ADXL05, Norwood, MA, datasheet, 1996
Table 1 The comparison of several gyroscopes in different phase [11–13]

<table>
<thead>
<tr>
<th>Gyro Type</th>
<th>Date</th>
<th>Size (in³)</th>
<th>Bias Stability (deg/hr)</th>
<th>Price (U.S. per axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic gyro (Rockwell Inc.)</td>
<td>1970s</td>
<td>50~100</td>
<td>0.02</td>
<td>17000</td>
</tr>
<tr>
<td>Expected near-term (navigation and military gyros)</td>
<td>1990s</td>
<td>10~20</td>
<td>0.02</td>
<td>5000~10000</td>
</tr>
<tr>
<td>Expected near-term (general consumer gyros)</td>
<td>1990s</td>
<td>0.01~1.0</td>
<td>10</td>
<td>1~10</td>
</tr>
</tbody>
</table>

Fig. 2 A simplified diagram of the Analog Devices’ accelerometer

(a) at rest

(b) Momentarily responding to an externally applied acceleration

Fig. 3 Overall structure of the system

Table 2 Definition of coordinate

<table>
<thead>
<tr>
<th>Name</th>
<th>Origin</th>
<th>X axis</th>
<th>Y axis</th>
<th>Z axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial coordinate</td>
<td>The center of the object</td>
<td>The cast is positive.</td>
<td>The north is positive.</td>
<td>The top is positive.</td>
</tr>
<tr>
<td>Earth coordinate</td>
<td>The earth’s core</td>
<td>Zero degree meridian</td>
<td>90 degree meridian</td>
<td>Earth axis</td>
</tr>
<tr>
<td>Geographical coordinate</td>
<td>Surface of the earth</td>
<td>The cast is positive.</td>
<td>The north is positive.</td>
<td>The top is positive.</td>
</tr>
<tr>
<td>Moving object coordinate</td>
<td>The center of the object</td>
<td>The front is positive.</td>
<td>The left is positive.</td>
<td>The top is positive.</td>
</tr>
</tbody>
</table>
Fig. 5 User interface